DETERMINATION OF CRITICAL CRACKING TEMPERATURE OF OIL SANDS AT LOW TEMPERATURE CONDITIONS

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

This research is intended to predict the viscoelastic behavior of oil sand mixes under low temperature conditions. The oil sand used in this project is a natural, unmodified material that was characterized to explore its unique attributes. A set of oil sand mixes was prepared in the lab with different oil sand content. Field prepared oil sand mixes with different content of oil sand were obtained and both the lab and field mixes were cut into thin beams. The stiffness and creep compliance values of the specimens were obtained through the BBR testing of samples at low temperatures of -18C, -12C and -24C. Time-temperature super position principle was applied in order to obtain a master creep stiffness curve for the oil sand mixtures. With the help of Laplace transformation, relaxation moduli for the mixtures were predicted. Based on the relaxation moduli and strain values, the thermal stresses of the oil sand mixtures were determined. After the thermal stress values were determined, the plots between temperature and stress were drawn. These plots provided the cracking temperatures for different percentages of oil sands in the mixes, which were used in the study. The key findings of this research are that the relaxation modulus of the oil sand mix increases with decrease in oil sand content and the critical cracking temperatures of the oil sand mixes are higher than that of the actual low pavement temperatures in Utah.

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LIST OF ABBREVIATIONS

BBR	Bending Beam Rheometer
SAP	Single Asymptote Procedure
SGC	Superpave Gyratory Compactor
TTSP	Time-Temperature Superposition Principle
LVE	Linear Viscoelastic Theory
TCR	Critical Cracking Temperature
AADT	Annual Average Daily Traffic
LTPP	Long Term Pavement Performance

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OIL SANDS BACKGROUND

Oil sands, tar sands or, more technically, bituminous sands, are a type of unconventional petroleum deposit. The oil sands are loose sand or partially consolidated sandstone containing naturally occurring mixtures of sand, clay, and water, saturated with a dense and extremely viscous form of petroleum technically referred to as bitumen (or colloquially tar due to its similar appearance, odor and color).

Much of the world's oil (more than 2 trillion barrels) is in the form of oil sands, although it is not all recoverable. While oil sands are found in many places worldwide, the largest deposits in the world are found in Canada (Alberta) and Venezuela, and much of the rest is found in various countries in the Middle East[1][2]. In the United States, oil sands resources are primarily concentrated in Eastern Utah, mostly on public lands. The in-place oil sands resources in Utah are estimated at 12 to 19 million barrels [3][4].

Figure 1shows the deposit locations within the state. There are six major deposits in the Uintah Basin. Other major deposits are located in the San Rafael Swell, the Circle Cliffs, and the Paradox Basin. The oil sand used for this research is from the Crown Energy’s Asphalt Ridge deposit in the Uintah Basin. Figure 2 shows the Asphalt ridge site. Uintah Basin oil sand was formed during the Cenozoic Era, around 34 – 56 million years ago.[5]

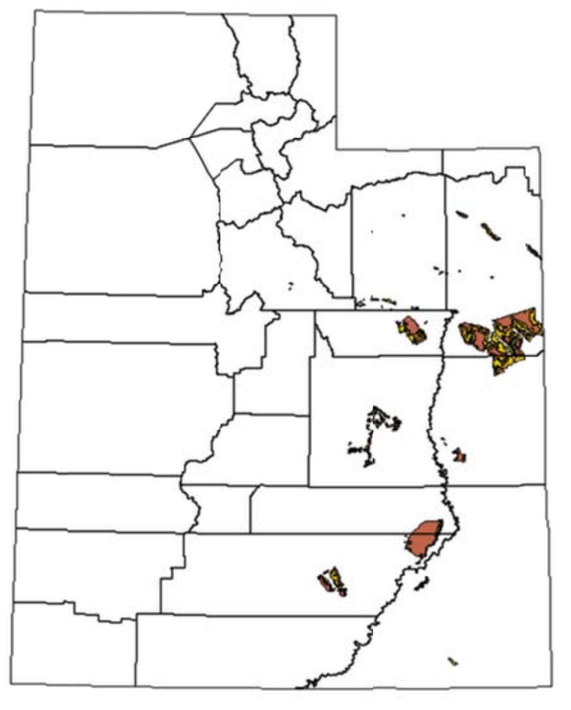

Figure 1-Oil Sand Reserves in Utah

Figure 2-Asphalt Ridge Deposits, Uintah, Utah

Oil sands reserves have only recently been considered to be part of the world's oil reserves, as higher oil prices and new technology enable profitable extraction and processing. Oil produced from bitumen sands is often referred to as unconventional oil or crude bitumen, to distinguish it from liquid hydrocarbons produced from traditional oil wells.

Oil sands can be mined and processed to extract the oil-rich bitumen, which is then refined into oil. This refining is more complex than the conventional oil recovery. The bitumen in oil sands cannot be pumped from the ground in its natural state; instead oil sand deposits are mined, usually using strip mining or open pit techniques, or the oil is extracted by underground heating with additional upgrading [1]. Oil sands recovery processes include extraction and separation systems to separate the bitumen from the clay, sand, and water that make up the oil sands. Bitumen also requires additional upgrading before it can be refined. Because it is so viscous (thick), it also requires dilution with lighter hydrocarbons to make it transportable by pipelines.

Advantages of Oil Sands

1. Large reserves available in USA as well as Canada which is close to USA.

Disadvantages of Oil Sands

1. Production cannot be ramped up as quickly as conventional oil production, owing to the operational processes used in deriving oil from the sands.
2. Extracting oil from oil sands entails high production costs and low net useful energy yields.
3. Production of oil from oil sands has high negative environmental impacts [6].

3. Production of oil from oil sands has high negative environmental impacts [6].

Since, it is economically not so feasible to extract bitumen from oil sands [7] and also it’s significant impact on environment [6], research had been conducted on using oil sands directly into the pavement mixture instead of traditional bitumen [9]. This research yielded good results and if it is used by the DOT’s to lay the road, it can save nearly $45,000 per mile of pavement construction [8].

Studies have revealed that thermal cracking occurs at very low temperatures when the aggregate base is in frozen condition and due to monotonic loading or fewer loading cycles of higher amplitude with respect to the strength of the material [10]. The thermal cracking has also been found to be one of the major distresses in asphalt pavements in northern U.S. and Canada [10]. The thermal cracking manifests itself as parallel surface initiated transverse cracks that are perpendicular to the center line of roadway [11]. The tensile stresses occurring due to lower temperature conditions when greater than the strength of the material are responsible for cracking. This in turn would result in deterioration of the pavement quality, reducing the life of the pavements. A good understanding of the cracking temperature would help in determining the optimum quantity of Oil sand that could be used in a particular region.

BENDING BEAM RHEOMETER (BBR)

The Bending Beam Rheometer (BBR) has been used for determining parameters like stiffness, m-value for the tested specimens. The thermal stresses in asphalt pavements have been calculated with the help of these parameters [12]. The oil sand mixture beams used for this study are sized 12.7mm x 6.35mm x 127mm (width x thickness x length) as required by the BBR for testing. It has been shown that the small samples of oil sand mixtures used for testing purposes and determining engineering properties are a representative of the mixture behavior. This approach allows for benefits like lower equipment cost, faster conditioning and sample testing, simplicity of test and the possibility of multiple replicate tests for statistical significance [13]. Research studies have demonstrated the effectiveness in considering BBR for estimating creep compliance and lower temperature properties [11][14]. Figure 3 shows testing of oil sand samples.

Figure 3-Oil Sand Mixture Testing in BBR

OBJECTIVES

The objectives of this research are to

1. Obtain mechanical properties of the oil sand mix at low temperature conditions using bending beam rheometer,
2. to find the critical thermal cracking temperatures and
3. to suggest the areas where these mix can be used to lay roads in Utah and surrounding states.

MATERIALS

A well-designed asphalt pavement will be able to carry the traffic loads for the duration of the duration of it design life. It should also provide adequate friction to the tires of the vehicle and should also be able to resist irregularities that develop as a result of traffic loading such as rutting, stripping, or potholing. Asphalt mixtures are made from oil sands and aggregates. A mix design is a process to find the right amount of binder and aggregates to make a mix that will be able to carry traffic loads and also resists irregularities. Many samples were taken into consideration for testing the stiffness of the oil sands. The mixes which were proven to be effective in the field are 60/40 and 67/33 mixes [9]. The 60/40 mix consists of 60% aggregate (and lime) and 40% oil sand, which were mixed at 240 ˚F, whereas 67/33 mix consisted of 67% aggregate (and lime) and 33% oil sand, which were mixed at 240 ˚F. The mix design of these samples is provided in Table 1. Lime was added in small quantity (0.57%) to the mixes to increase the binding property of oil sands with the aggregate. Table 2 shows the aggregate composition. In the 60/40 mix, out of total 60% aggregate composition, 45.58% of aggregate is of ¾” inch and the rest is 13.85% is of ½” inch. In 67/33 mix, 49.55% of aggregate is of ¾” inch and 16.87% of aggregate is of ½” inch totaling it to 67% (including lime). The source of aggregate for the mix design is taken from Maser East pits, Vernal, Utah and the sample size and aggregate distribution are provided below in Table 3 and Table 4, respectively.

Table 1-Material Composition

	60/40	67/33
%lime	0.57	0.57
% Oil sand	40.00	33.00
% virgin Aggregate	59.43	66.43
Total	100.00	100.00

Table 2- Aggregate Distribution

% Agg	60/40	67/33
%3/4	45.58	49.55
%1/2	13.85	16.87

Table 3-Mix Size

	60/40	67/33
Aggregate Source	Maser East	Maser East
Total sample size (g)	4800	4800
Total Aggregate size (g)	2852.6	3188.88

Table 4- Aggregate Distribution

Type of Aggregate		60/40		67/33
	Weight (g)	Cumulative Percent Distribution	Weight (g)	Cumulative Percent Distribution
¾”	0	0%	0	0%
½”	1233.5	43%	1342.1	42%
3/8”	928.5	76%	1029.2	74%
#4	568.5	96%	678.3	96%
#8	34.5	97%	41.1	97%
#16	0	97%	0	97%
#30	9.2	97%	10.4	97%
#50	5	97%	5.6	97%
#100	14.3	98%	15.9	98%
#200	26.5	99%	29.5	99%
-#200	32.5	100%	36.7	100%

The mixes were prepared by mixing virgin aggregates with the oil sand. After the mixing of these components, the Superpave Gyratory Compactor (SGC) was used for compacting of the mixes. These compacted mixes were frozen for a minimum of 4 hours. The frozen compacted mixes were then cut into thin beams of size of 12.7mm x 6.35mm x 127 mm (width x thickness x length) using a lapidary saw and a smaller tile saw. The beams dimensions and weight were noted and appropriate labeling was carried out. The average densities of the mixes were provided in Table 5. These thinly cut beams were then taken to the BBR for testing purposes. Before the commencement of testing, the beams were placed in the BBR bath for 60 minutes. The testing was carried out in conformance with AASHTO T313 *Standard Test Method for Determining the Flexural Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)* [13]. At least 15 samples for each mix design were tested using a three-point bending test in BBR. The test gives the deflection from which the creep stiffness is calculated. The creep stiffness is defined as the ratio of constant stress over time dependent strain. This is analogous to the modulus of the material. The results also include m-values of the samples, which is the slope of the stiffness versus time curve. The stiffness and deflection values as a function of time along with the dimensions of each specimen were taken for further analysis. After testing was done, all samples were analyzed and outliers were eliminated. To eliminate the outliers, the creep stiffness at 60 seconds was used as quality control. The values were

Table 5-Average Density of Oil Sand Mixes

	No.of Samples	Avg.Density (gm/mm^3)	St.dev	C.V (%)
60/40_P	11	0.265498	0.007595	2.86%
67/33_P	12	0.305941	0.01561	5.10%
60/40	12	0.264401	0.005664	2.14%
67/33	12	0.287196	0.009855	3.43%

ordered from high to low and the extremes were systematically eliminated until the coefficient of variation of the measured creep stiffness was below 10%. Previous work has shown that the results should follow a normal distribution [13]. The elimination of high and low resulted in a trimmed mean that more closely matched the normal distribution. Around three samples were eliminated in each mix to attain the coefficient of variance below 10% which left 12 samples for the mean. The temperatures used for testing were -12 C, -18 C and -24 C. The force applied during the three-point bending test for each specimen and the deflection value obtained as a result was used for calculating creep compliance for that particular specimen. As explained in the methodology, creep compliance is defined as the time dependent strain over constant stress. It is the inverse of creep stiffness. The creep compliance values of all the tested specimens at different low temperature conditions were used for conducting linear viscoelastic analysis and stress calculations.

METHODOLOGY

The aim of the research is to determine the effect of low temperature on the lab prepared oil sand mixes and compare the results to that of the plant mixtures.

The following procedure has been carried out for determining the effect of low temperature:

1. The deflection values obtained for each of the samples tested were used to calculate creep stiffness values at the lower temperatures. The equation for creep stiffness is:

   $$S(t)=\frac{PL3}{4bh3\delta(t)}$$

   where:

   S(t)= asphalt binder stiffness at a specific time

   P= applied constant load (4410mN)

   L= distance between beam supports (102mm)

   b= beam width

   h= beam thickness

   δ(t)= deflection at a specific time.

   These creep stiffness values were converted to creep compliance values by taking the inverse of them which is a common practice in the BBR analysis [12].

From Table 6, we can notice the coefficient of variation (CV) of creep stiffness at 60 seconds testing, of all the mixes was less than 10%.

2. The master compliance curves for each mix design were prepared based on the time-temperature superposition principle (TTSP). TTSP has been used in order to provide an extended time domain for compliance curves on a log of compliance versus log of reduced time scale. The reduced time is calculated based on the shift factor, which is calculated with the help of Arhennious function considering -18 C as the reference value.
3. Following the preparation of master compliance curves, a presmoothing technique was carried out in order to fit the experimental data. The fitting process included generating Power law parameters to be used in a generalized power function. This process involved use of nonlinear regression techniques.

Table 6-Coefficient of Variation of the Mixes

		No. of Samples	Avg. Creep Stiffness (MPa)	Std.Dev	C.V (%)
60/40	T1	12	9,250.0	906	9.79%
	T2	12	17,528.0	1,720	9.81%
	T3	12	22,021.0	2,190	9.95%
67/33	T1	12	7,650.0	678	8.86%
	T2	12	14,133.0	1,364	9.65%
	T3	12	20,431.0	1,985	9.72%
60/40_P	T1	11	6,796.0	561	8.25%
	T2	11	10,148.0	891	8.78%
	T3	11	21,965.0	1,876	8.54%
67/33_p	T1	12	6,891.0	671	9.74%
	T2	12	10,716.0	1,041	9.71%
	T3	12	22,012.0	2,016	9.16%

4. The generated power law parameters were used in the power law function to determine a generalized equation for creep compliance as provided below: Power Law Function:

$$D(t) = D_0 + D_1 * t^n \qquad (1)$$

where,

D(t) = creep compliance at reduced time, t and

D0,D1,n = power law parameters

5. The Laplace transformation of creep compliance was done in order to obtain relaxation moduli of all specimens under different temperature conditions.
6. The relaxation moduli being a function of time needed to be converted to a function of temperature. This was done using the regression equation between temperatures and shift factors, which was obtained with the help of TTSP.
7. The relaxation moduli as a function of temperature was used to calculate stresses through the equation:

$$\sigma(T) = \int_0^T E(T - T') * \frac{\partial \varepsilon(T)}{\partial T'} * dT' \qquad (2)$$

where,

σ(T)= Thermal stresses at temperature T

E(t)= relaxation modulus at temperature T

ε(T)= Strain at temperature T

T’= dummy variable or variable of integration

Here strain $\varepsilon(T) = \alpha$ (coefficient of thermal contraction) x dT/dt (temperature increment)

8. The stresses obtained for each mix design were compared in the form of plots of thermal stresses versus temperature and the cracking temperature was determined.

TIME-TEMPERATURE SUPERPOSITION PRINCIPLE

The intent of time temperature superposition principle (TTSP) is to indicate the dependence of viscoelastic materials on the temperature conditions in which they are tested. This concept has been used in order to shift individual compliance curves at various temperatures and formulate a master creep compliance curve by using the concept of shifting time scales with the help of shift factors [11][13][14]. The TTSP has been used for illustrating the notion that the response time function of creep compliance values at a certain temperature would be similar to the response time functions of nearby temperature values. The method of reduced variables or TTSP overcomes the difficulty of extrapolating limited laboratory tests at shorter times, to longer-term, more real-world conditions. The TTSP is based on direct equivalency between time and temperature [16]. Figure 4 shows the graphical representation of TTSP.

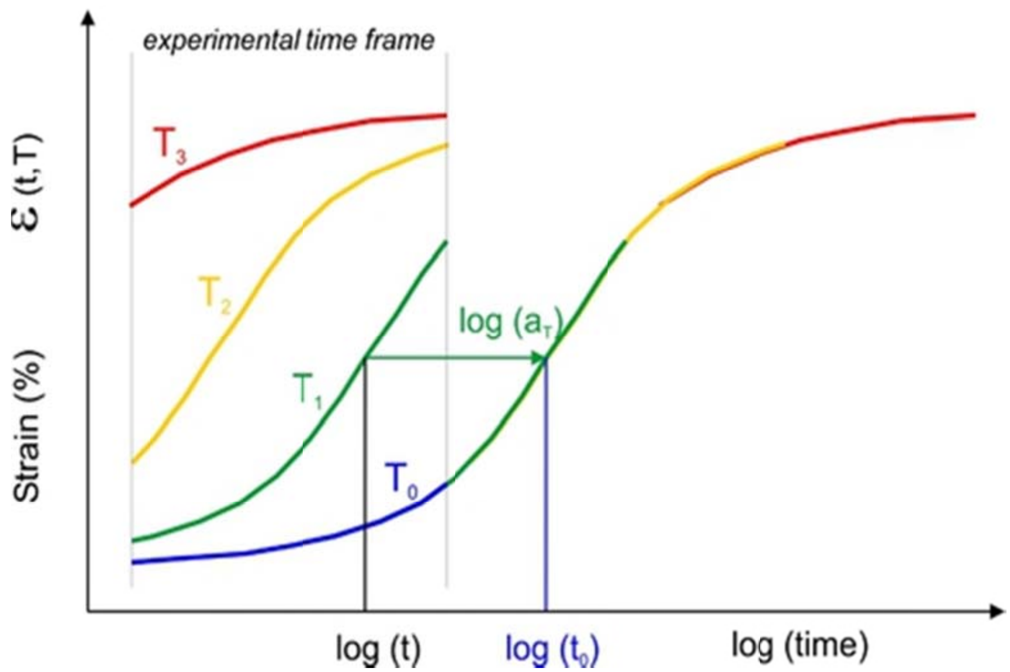

Figure 4-Time Temperature Superposition
(www.skz.de)

MASTER CURVE GENERATION

The transposing of creep compliance data at adjacent temperatures results in a master curve with which the material property of interest at a specific end-use can be predicted over a broad time-scale [16]. The processes involved in the generation of master curves during this study are as follows:

1. Creep compliance values were obtained for every percentage of oil sand tested at three temperatures -12 C, -18 C and -24 C under constant loading conditions.
2. These compliance values at all the three temperatures were plotted against time scale for each mix design as indicated in Figure 5 and Figure 6. Of the three temperatures, -18 C was taken as a reference temperature for every percentage of oil sand tested.
3. Following the creep compliance versus time plotting, shift factors were determined. The shift factor is used to convert real time to reduced time in order to broaden time-scale. The Arrhenius function that serves the intent of establishing a relation between the shift factors and temperature under a reference temperature was used for this purpose [17]. The function has been illustrated as:

$$\text{Log}[aT(T)] = 2.303\, \frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{Tr}\right) \tag{3}$$

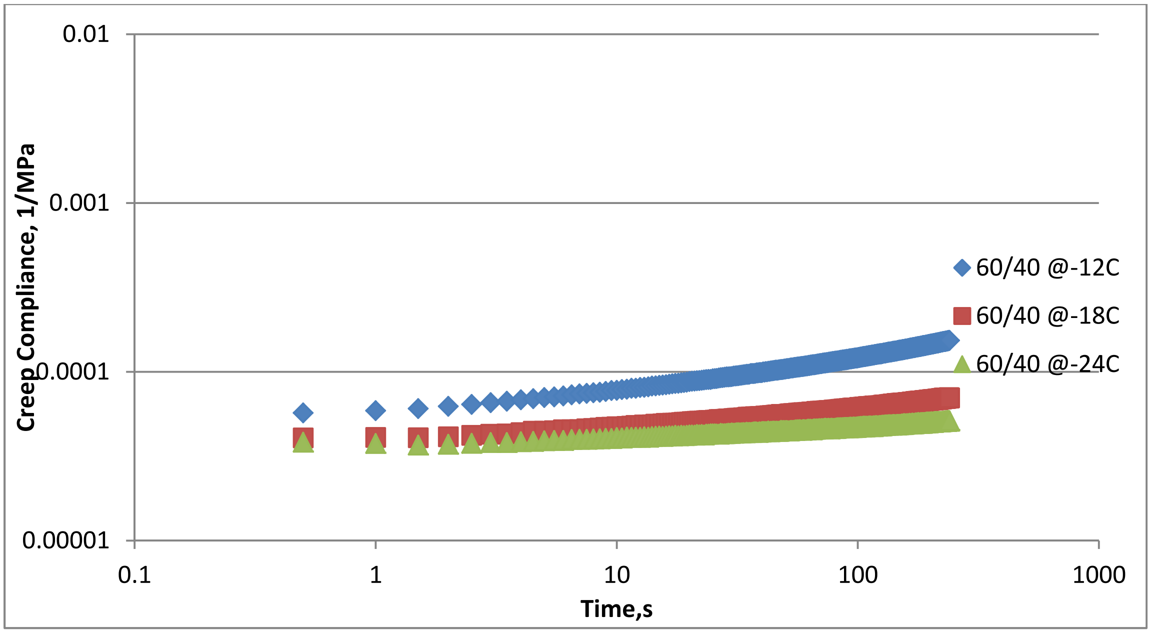

Figure 5-Individual Compliance Curves for 60/40 Lab Mix

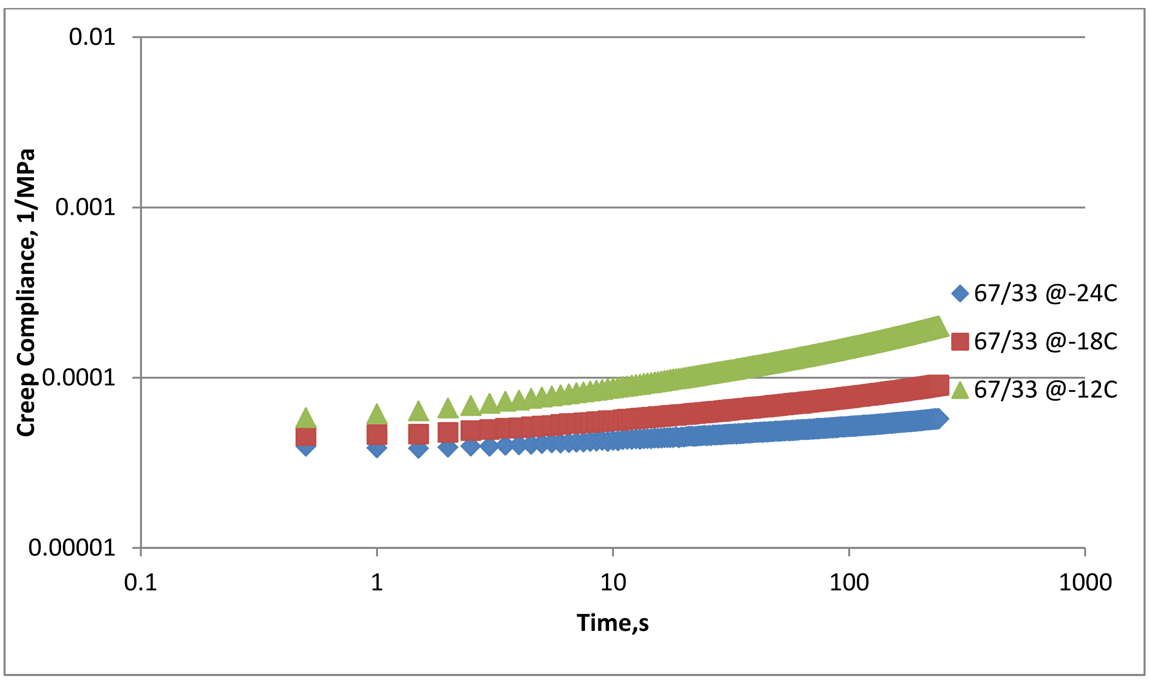

Figure 6-Individual Compliance Curves for 67/33 Lab Mix

where, Ea= the activation energy for flow below TR, 261 kJ/mol.

R= the ideal gas constant, 8.34J/mol-°K

TR = referenced temperature, °C or °K

T = reference temperature, °C or °K

4. The reduced time can be represented using temperature and shift factor parameters as below:

$$\xi = \frac{T}{aT(T)} \tag{4}$$

where ξ = reduced time for non-constant temperatures

aT (T) =shift factor

and T =temperature

The reduced time can also be represented in terms of real time t and temperature T as shown below:

$$\xi = \int \frac{dt}{a(T)} \tag{5}$$

5. The shift factor was used to determine the reduced time for the corresponding temperatures with regards to every percentage of oil sand considered for testing. The shift factor versus temperature relation has been shown in Figure 7 and Figure 8.
6. The calculation of reduced time through shift factor provided a broad time-scale with the help of which master curves were generated in Figure 9 and Figure 10.
7. The creep compliance values obtained from the master curve were used to determine the power law parameters by fitting the experimental data using the

presmoothing technique that required the employment of nonlinear regression methods.

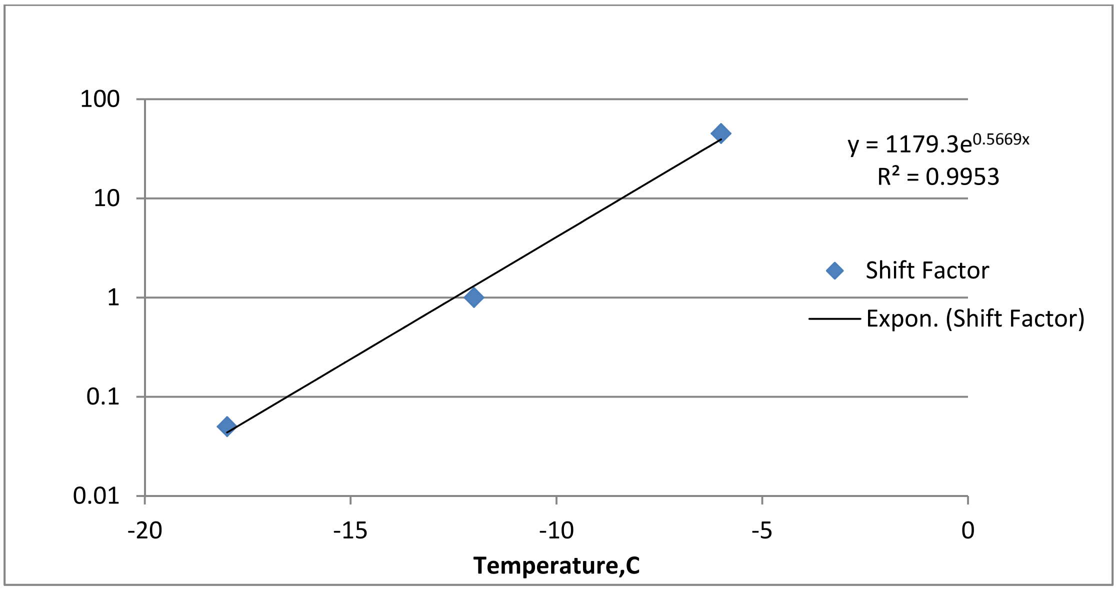

Figure 7-Shift Factor for 60/40 Lab Mix

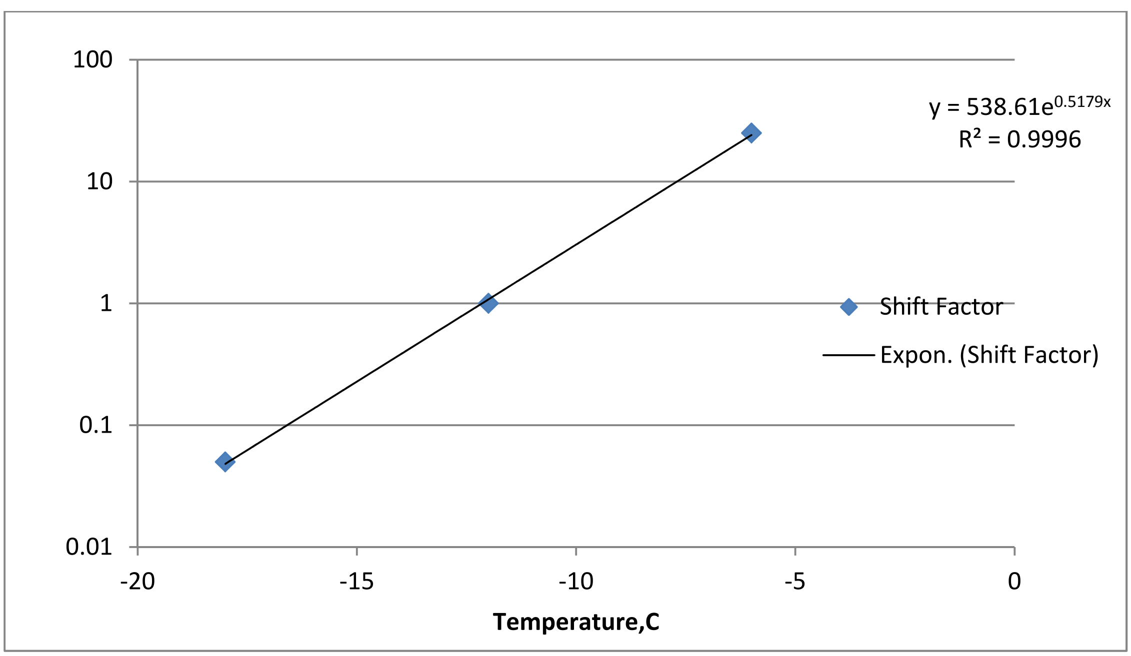

Figure 8-Shift Factor for 67/33 Lab Mix

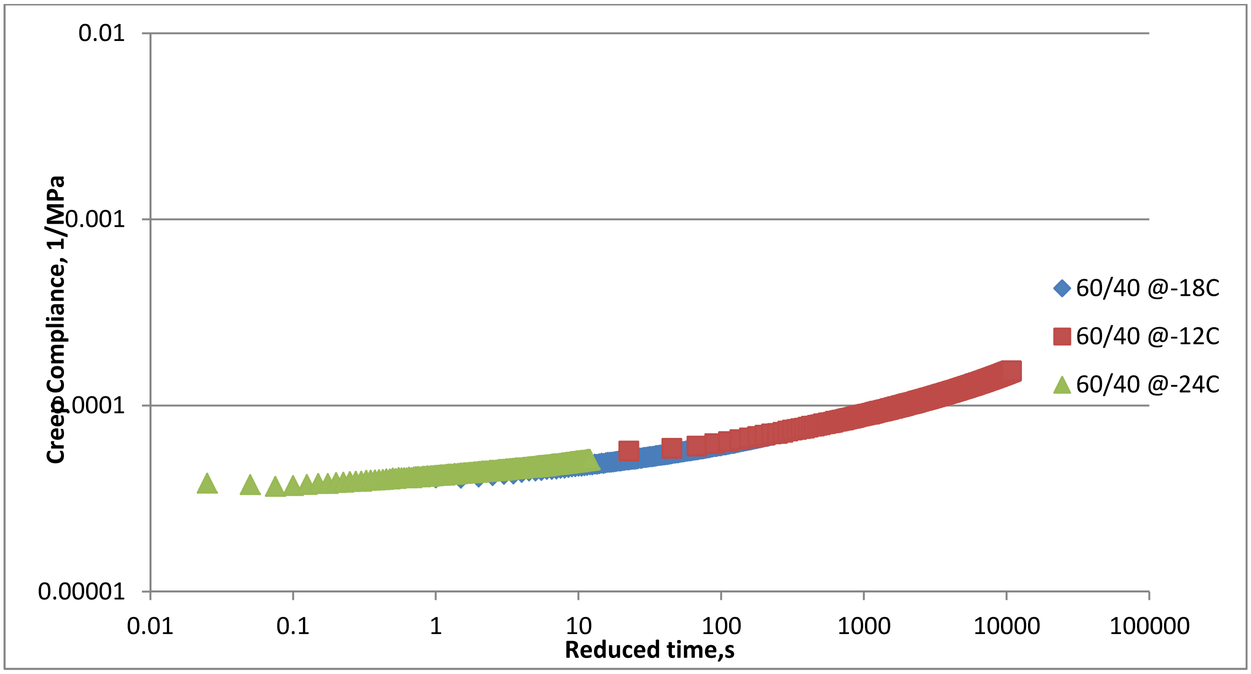

Figure 9- Master Curve for 60/40 Lab Mix

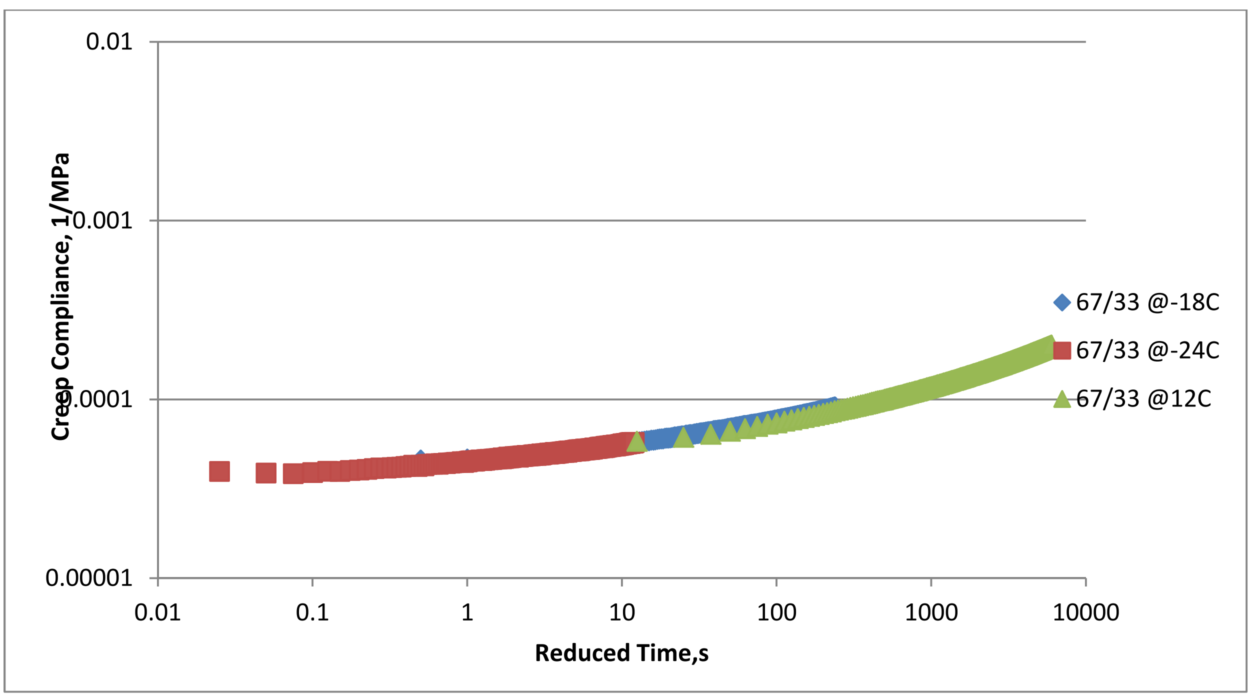

Figure 10-Master Curve for 67/33 Lab Mix

PRESMOOTHING TECHNIQUE

The presmoothing technique was carried out in order to obtain a smooth curve as opposed to the overlapping creep compliance curves which constituted the master compliance curve. This method required minimizing the sum of squared errors between the raw and fitted compliance values by means of nonlinear regression methods [13].

The expression for minimizing the errors is as follows:

Minimize $\Sigma|Dp\ (\xi)\ -\ D(\xi)|^2$ (6)

where $D_p(\xi)$ = fitted power law response at reduced time, ξ

$D(\xi)$ = raw experimental data at reduced time, ξ

The values of D_0, D_1, and n were determined for every percentage of Oil sand (Table 7) based on the pre smoothing technique.

The plots showing fitted curves and the raw data are shown in Figure 11 and Figure 12. It can be observed that the curves obtained from experimental data fit the raw data. The fitted data would be used to determine relaxation moduli followed by the thermal stress values and the cracking temperature, TCR.

Table 7-Power Law Parameters for Lab Mixes

	60/40	67/33
D_0 (1/Mpa)	4.31E-05	4.31E-05
D_1 (1/Mpa)	2.71E-06	4.82E-06
N	0.4	0.4

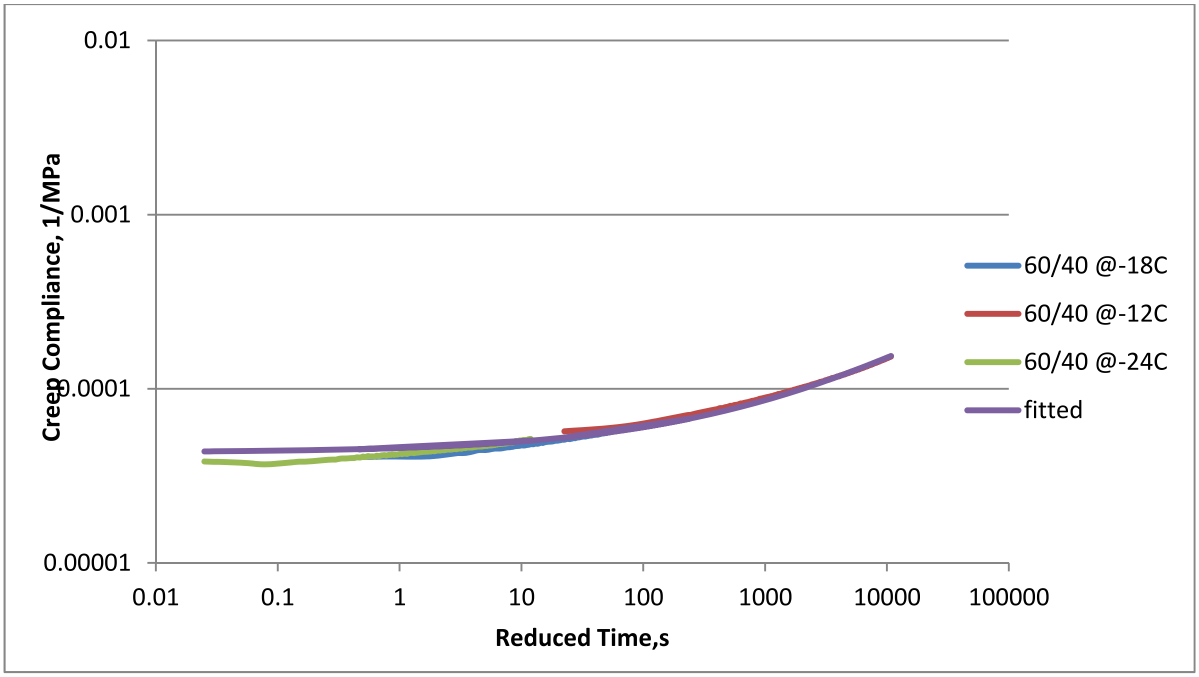

Figure 11-Power Law Fitting Approach 60/40 Lab Mix

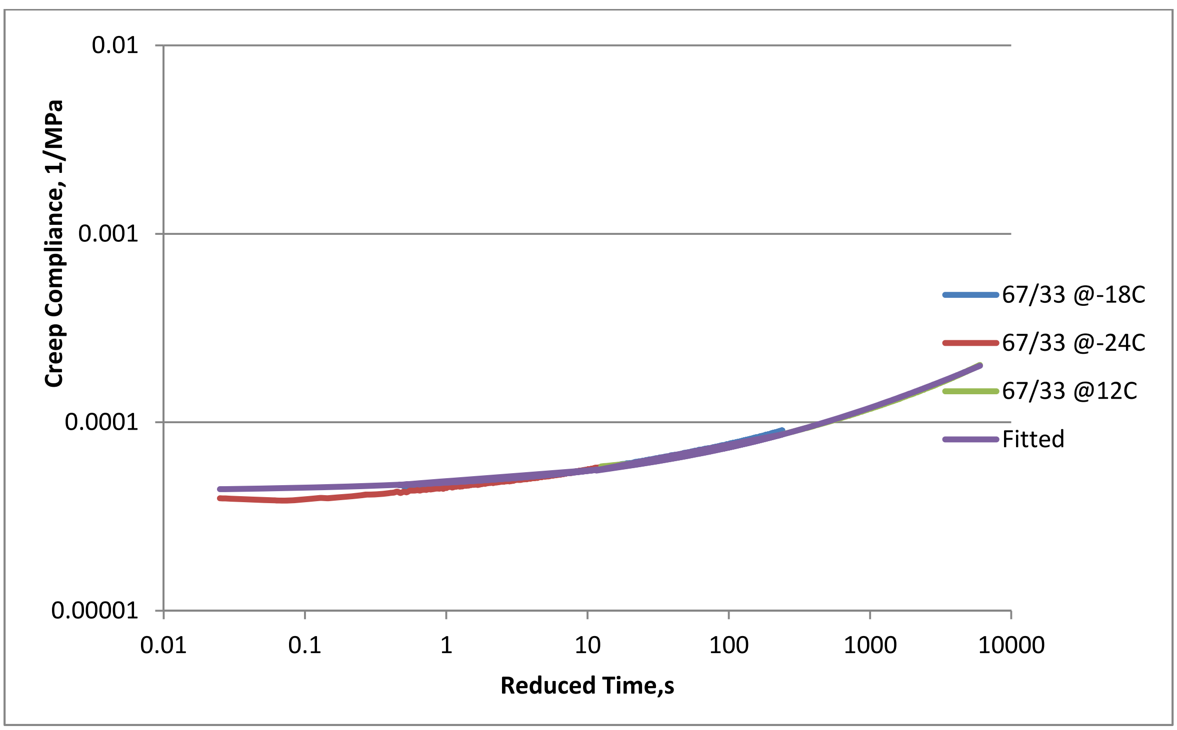

Figure 12-Power Law Fitting Approach 67/33 Lab Mix

MODELING THE LINEAR VISCO ELASTIC RESPONSE

The behavior of hot mix asphalt (HMA) can be adequately represented by linear viscoelastic theory (LVE) on the basis of accuracy in the inter conversion between the viscoelastic functions (creep compliances, relaxation moduli, etc.) used[18]. In the previous research studies conducted, the LVE has been used to predict the mechanical behaviors of asphalt concrete [13][14][15][19]. The linear viscoelastic behavior of asphalt mixtures has been characterized based on the average responses of all specimens tested during the BBR test [13]. In order to determine the thermal stress values corresponding to varying temperatures, the relaxation moduli as a function of temperature need to be determined. The relaxation modulus is obtained when the testing is done with constant stain. But the creep compliance value obtained in this testing is based on constant stress. So, in order to get relaxation modulus from creep compliance, the Laplace transformation [19] was used. The relaxation modulus can be related to creep compliance with the help of equation:

$$\bar{D}(\mathrm{S})\bar{E}(\mathrm{S})=\frac{1}{\mathrm{S}2} \tag{7}$$

where D(s) and E(s) are the Laplace transforms of creep compliance, D(t) and relaxation modulus E(t) respectively. By recalling the power law function equation we have:

$D(t) = D_0 + D_1*t^n$

Taking the Laplace transform of power law function, we get the equation

$$\bar{D}\ (S) = \frac{D0}{S} + D_1 \frac{\Gamma(n+1)}{S(n+1} \quad (8)$$

where Γ(n+1) is the gamma function of argument (n+1).

From equations (7) and (8), we have

$$\bar{E}(S) = \frac{1}{sD0+D1\Gamma(n+1)t\text{^}(1-n)} \quad (9)$$

To solve for E(t) the equation (8) needs to be inverted. This can be done using the 'direct method' proposed by Christensen [20], which would result in the equation provided below:

$$E(t) = \frac{1}{D0+D1\Gamma(n+1)(1.73t)n} \quad (10)$$

Another approximate method from Schapery [21] could also be used for inverting equation (8) and would result in a relation between E(t) and power law parameters as below:

$$E(t) = \frac{1}{D0+D1\Gamma(n+1)(1.786t)n} \quad (11)$$

The comparison plot showing the variation of relaxation moduli versus reduced time for different oil sand percentages is shown in Figure 13.

It can be observed from Figure 13 that the relaxation modulus increases for every decrease in the percentage of oil sand.

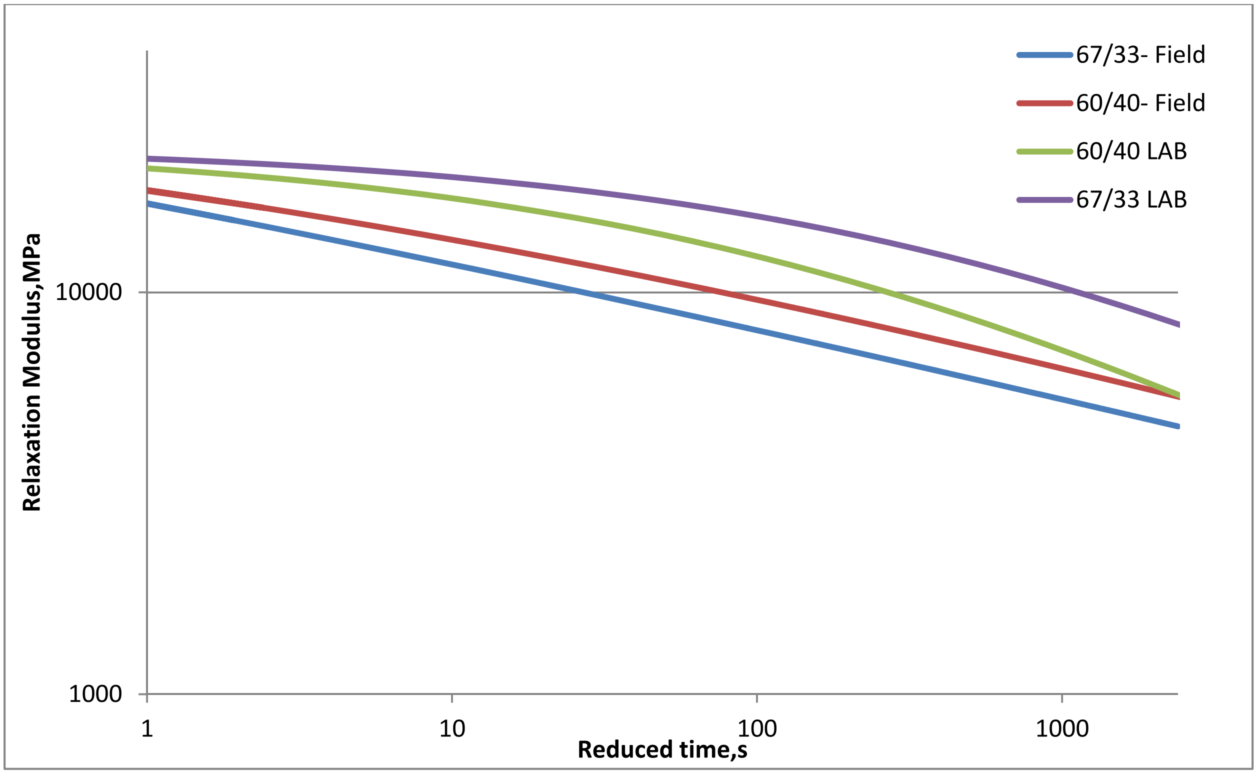

Figure 13- Relaxation Modulus vs Reduced Time

THERMAL STRESS CALCULATION

It is well known that thermal cracking of asphalt pavement is associated with cold temperatures during the winter months which cause thermal stresses in asphalt pavement. Asphalt pavement is a heterogeneous material; the asphalt binder in pavement will contract more than the mix aggregates particles when temperature drops. This causes the asphalt film to get thinner around aggregates. When temperature drops below where the asphalt binder becomes brittle, thermal cracking is initiated in the asphalt pavement. In other words, a thermal crack is formed when the strength of the asphalt pavement is less than the thermal stress caused by temperature drop. Figure 14 shows a typical thermal crack in asphalt pavement.

Figure 14-Thermal Crack in Asphalt Pavement

The calculated relaxation moduli being a function of time needed to be converted into a function of temperature in order to determine the thermal stresses as a function of temperature. This is done with the help of mathematical relation between shift factor, aT(T) and temperature T obtained through TTSP [13]. Recalling equation (2), the thermal stresses can be calculated as below:

$$\sigma(T)= \int_0^T E(T - T') * \frac{\partial \varepsilon(T)}{\partial T'} * dT'$$

The strain ε(t) is equal to the product of coefficient of thermal contraction (α) and the temperature increment (dT/dt). The recommended values of coefficient of thermal contraction (α) and temperature increment (dT/dt) are 1.7 x 10-4 mm/mm/C and 1 C per hour respectively for freeze regions [22]. The relaxation modulus calculated earlier along with the recommended values of coefficient of thermal contraction (α) and temperature increment (dT/dt) were substituted in the stress equation (Eq. 2) in order to determine the thermal stresses as a function of temperature.

DETERMINATION OF CRITICAL CRACKING TEMPERATURE, T_{CR}

In order to determine the critical cracking temperature, two methods have been proposed by Marasteanu[22] and Bouldin [22]to estimate the temperature from the thermal stress plot. The first method is the Single Asymptote Procedure (SAP) [22]. In this procedure, the thermal stresses were plotted against temperature in order to obtain the thermal stress curve. The intersection of the asymptote to the thermal stress curve; and the horizontal temperature axis provided the value of critical temperature, TCR. The critical temperature, TCR values for each mix design, has been shown in Figure 15 and Figure 16.

Through another method, the critical cracking temperatures can be obtained if it is assumed that the strength of asphalt mixtures of is 3 MPa [23]. The values on the horizontal (temperature) axis corresponding to the points of intersection of the asphalt mixture strength of 3 MPa to the thermal stress curve provided the TCR values. The plot for determining the cracking temperature through strength of asphalt mixtures is shown in Figure 17 and Figure 18.

From both the aforesaid methods used for determining critical temperature, TCR in this study, the values of TCR were in compliance and it could also be noted that there is a slight increase in the cracking temperature, TCR with the decrease in the percentage of oil sands in the mixtures (Table 8).

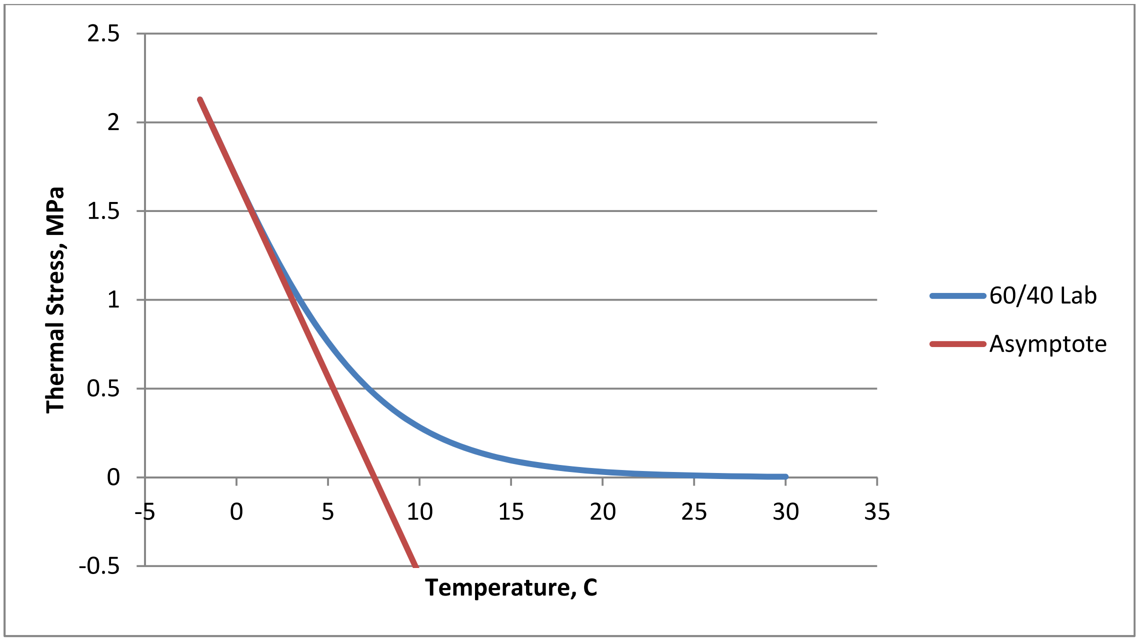

Figure 15-SAP Method- 40% Oil Sand

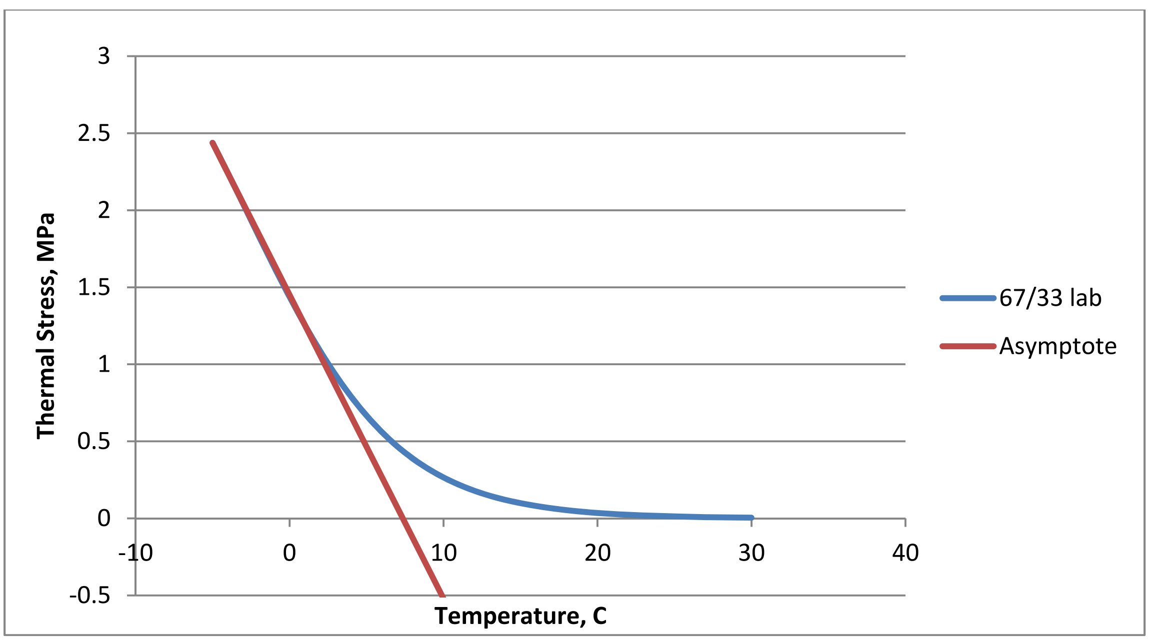

Figure 16-SAP Method-33% Oil Sand

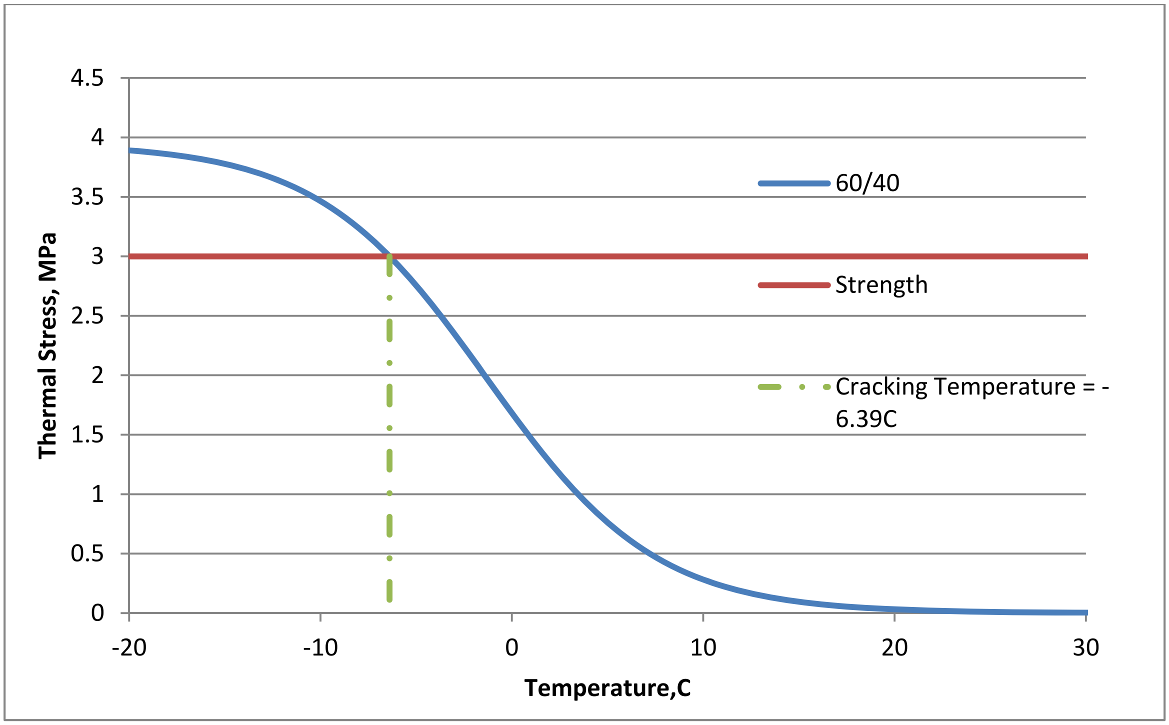

Figure 17-Strength Method- 40% Oil Sand

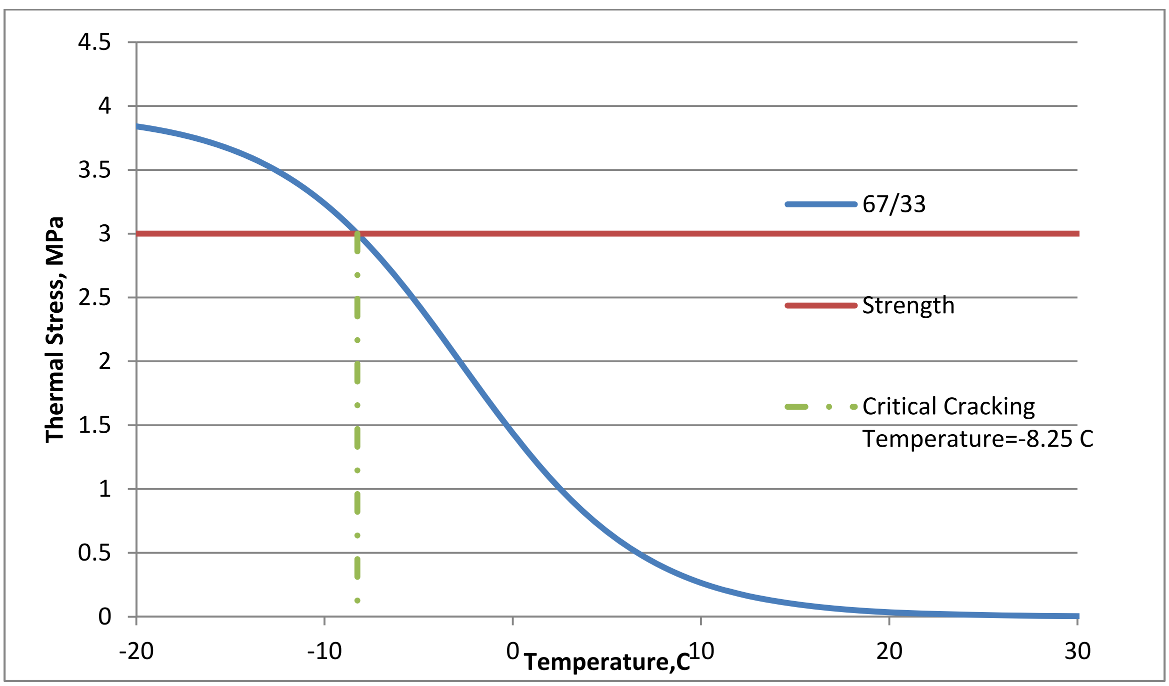

Figure 18-Strength Method- 33% Oil Sand

Table 8-TCR Comparison for Lab Mixes

Mix Name	TCR corresponding to asphalt mixture strength of 3 MPa, ˚C	TCR through single asymptote procedure (SAP), ˚C	Difference in TCR values from strength method and SAP method
60/40	-6.39	7.52	13.91
67/33	-8.25	7.35	15.70

TESTING OF OIL SAND PLANT MIXTURES

Once the lab samples were analyzed, field data were used to verify the results. Samples of oil sand mixtures prepared in a plant with 40% and 33% oil sand content were obtained, and testing and analysis was carried out. Bulk mixing was carried at the plant to prepare the mixes whereas mixes of smaller quantity were used for testing in the laboratory. This led to some variations observed between plant and lab mixtures. The individual compliance curves and the corresponding master curve for plant mixtures are shown in Figures 19-22.

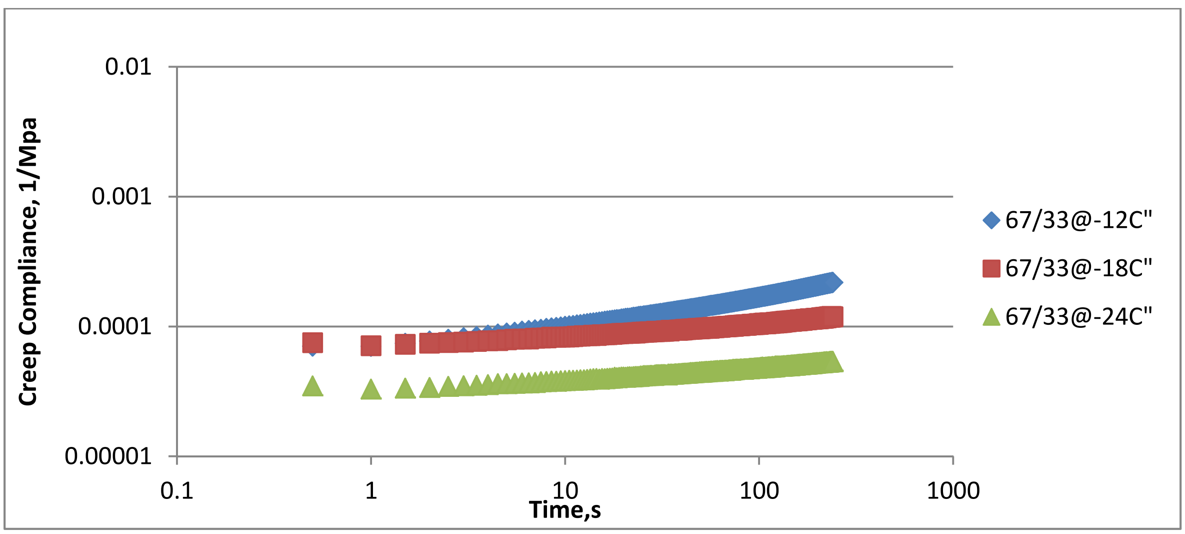

Figure 19-Individual Compliance Curves for 60/40 Plant Mix

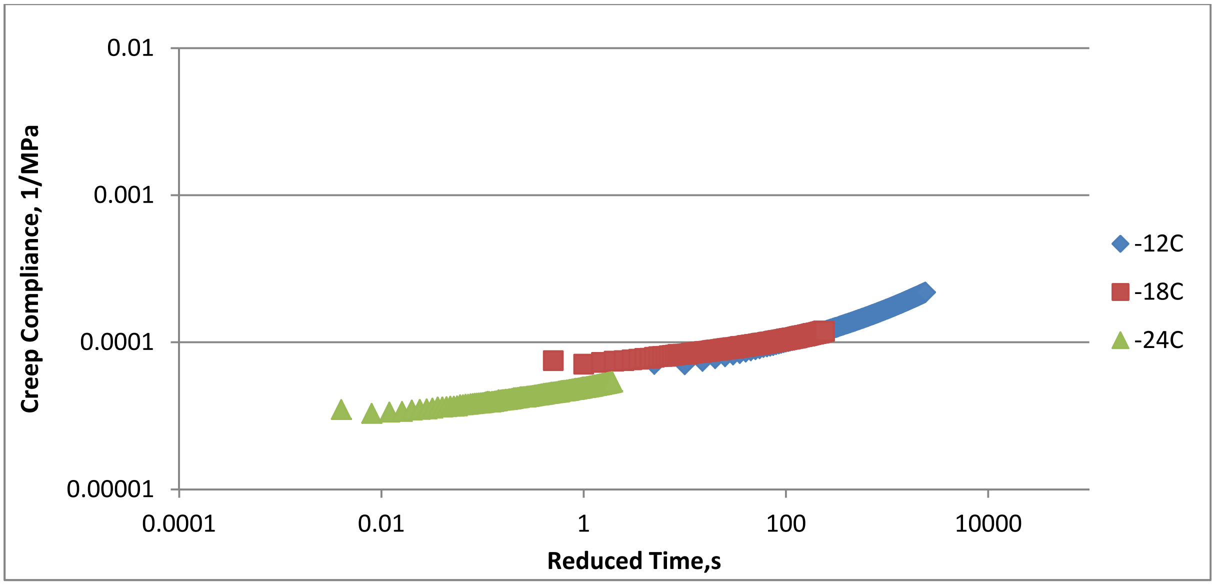

Figure 20-Individual Compliance Curves 67/33 Plant Mix

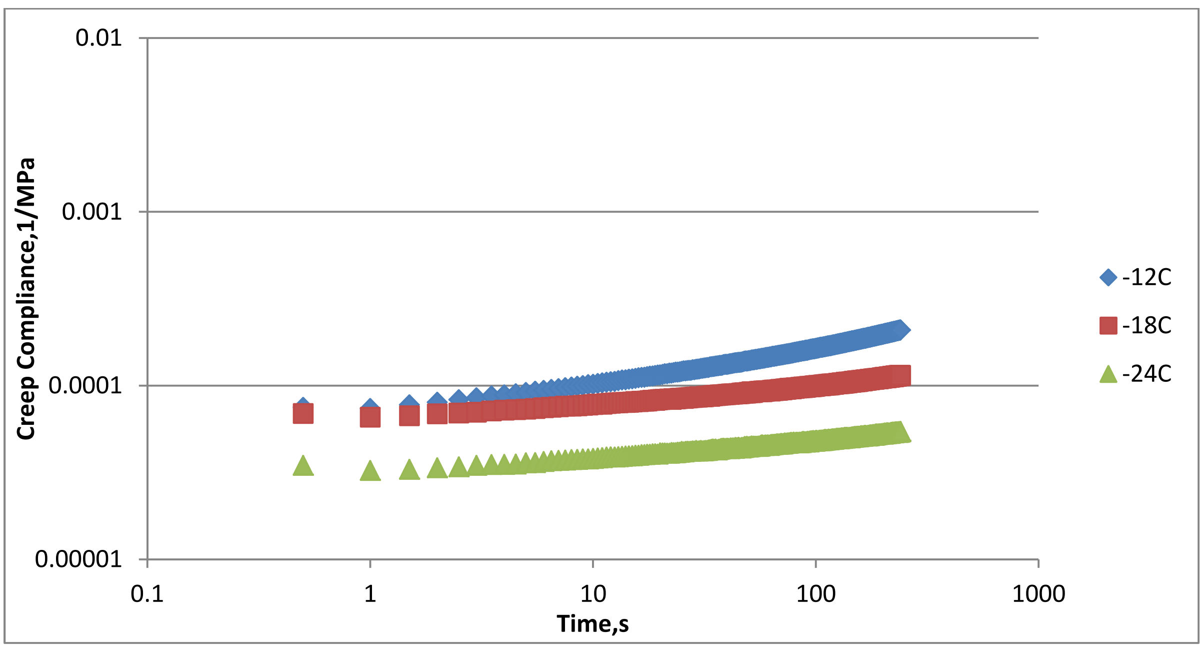

Figure 21-Individual Compliance Curves- 60/40 Plant Mix

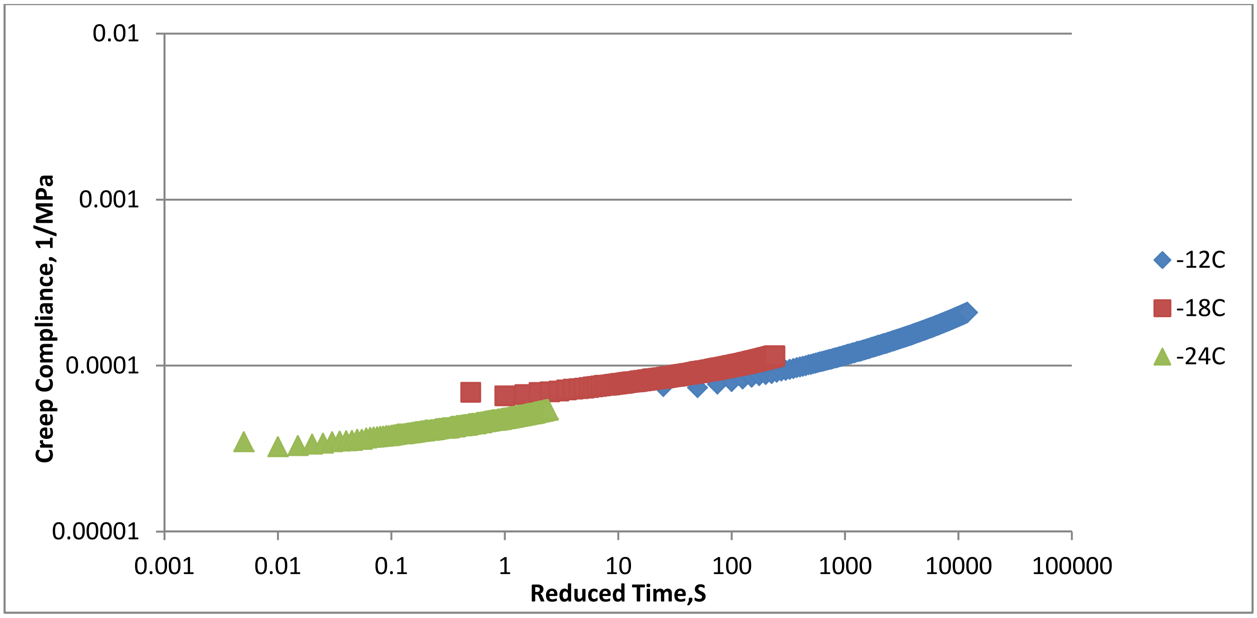

Figure 22-Individual Compliance Curves for 60/40 Plant Mix

The power law fitting approach was carried out for the plant mixture similar to that of lab mixtures. As a part of this power law fitting approach, a curve was fitted to the experimental creep compliance data for the plant mixtures obtained with the help of BBR testing. The experimental and fitted curves have been illustrated in Figure 23 and Figure 24. The power law fitting approach helped in generating power law parameters D0, D1 and n that were the variables for power law function. The values of parameters generated have been provided in Table 9.

Table 9-Power Law Parameters for Plant Mixes

Power Law Parameters	67/33 Plant	60/40 Plant
D_0	1.42E-05	2.79E-05
D_1	4.11E-05	2.44E-05
n	0.19	0.22

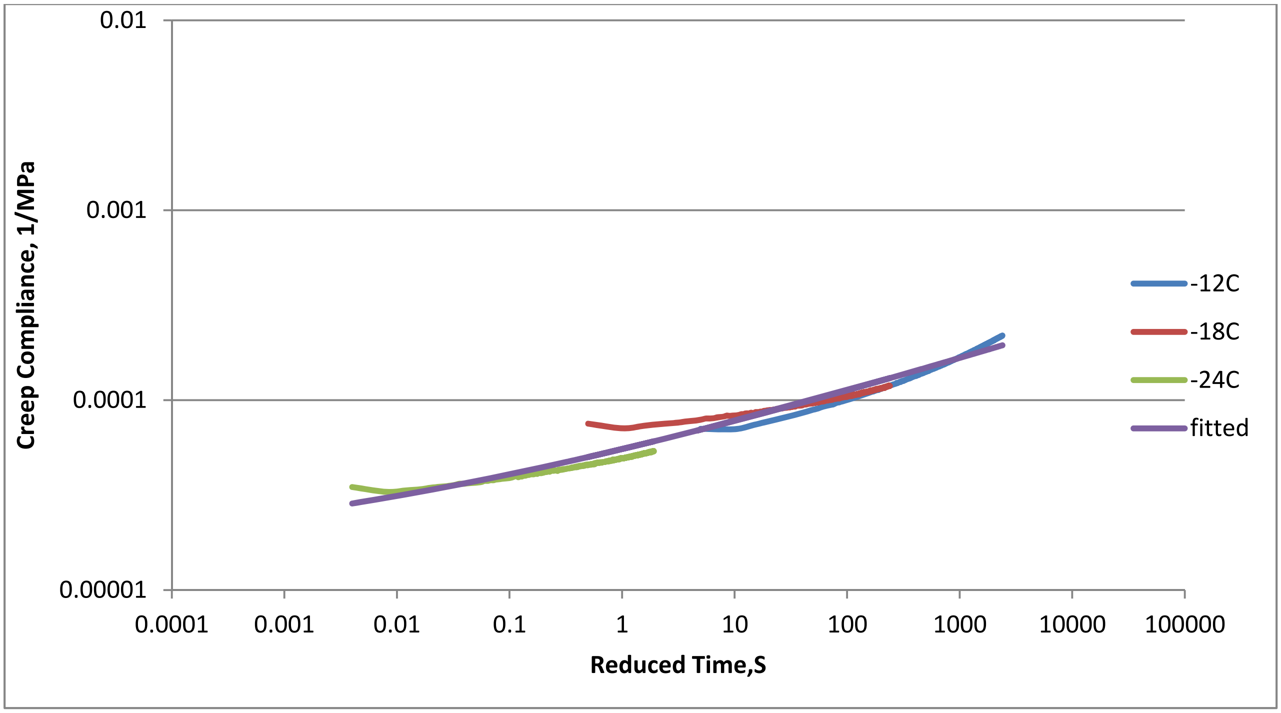

Figure 23-Power Law Fitting Approach for 67/33 Plant Mix

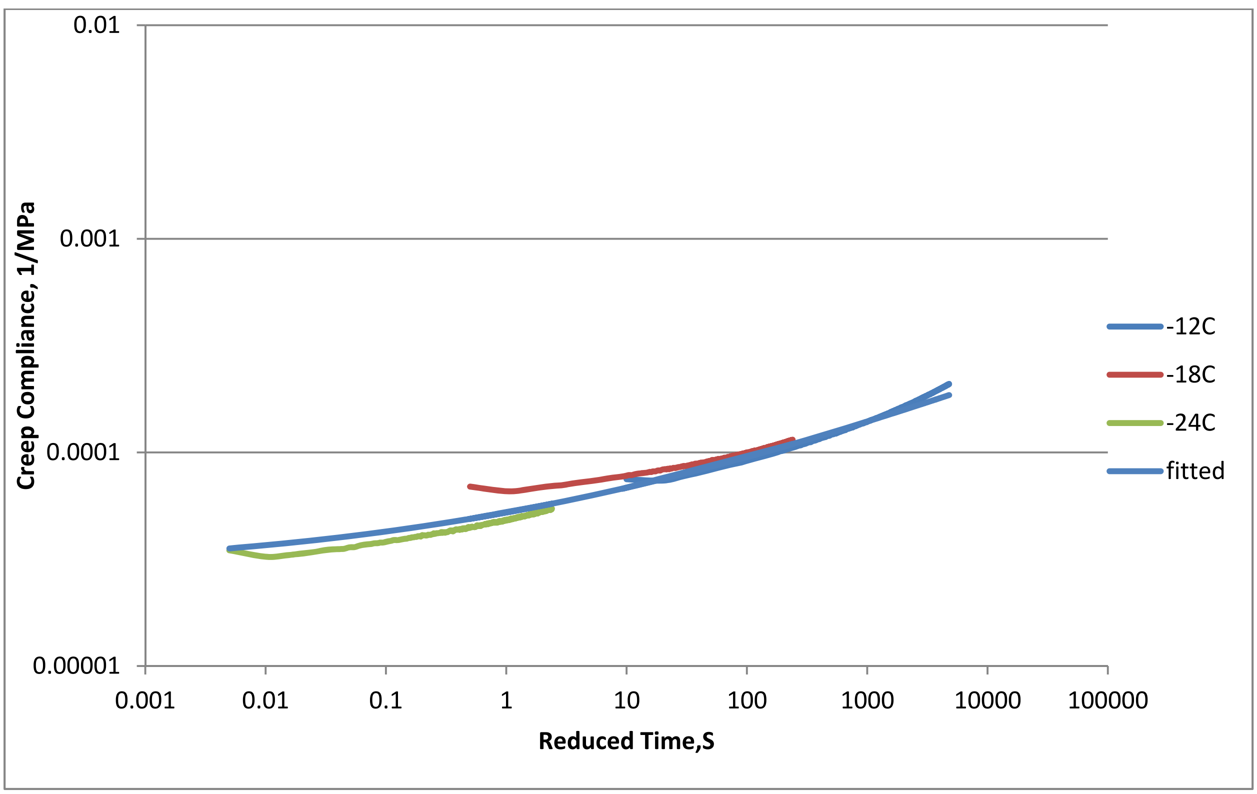

Figure 24-Power Law Fitting Approach 60/40 Plant Mix

During the next step, the relaxation moduli for plant mixtures were calculated with the help of the power law function which required the values of power law parameters obtained using the power law fitting approach. The graphs of relaxation modulus versus reduced time for plant mixtures are shown in Figure 25 and Figure 26. After the relaxation modulus values were determined for the plant mix, the thermal stress values were calculated using the thermal stress equation. Following this, the critical cracking temperature, TCR for the plant mix, was calculated with the two methods – SAP method and strength method, which were used for determining the same lab mixtures. The thermal stress curve and the critical cracking temperature, TCR for plant mix, obtained using the two aforesaid methods are illustrated in Figures 27 through 30.

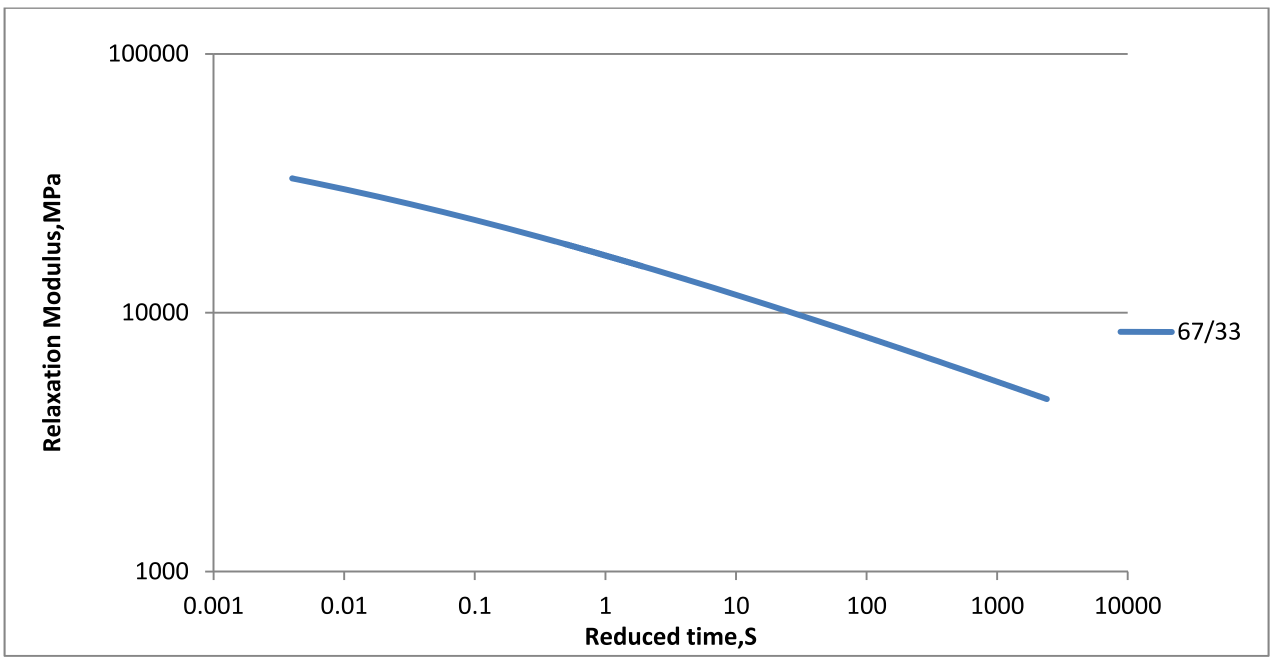

Figure 25-Relaxation Modulus-67/33 Plant Mix

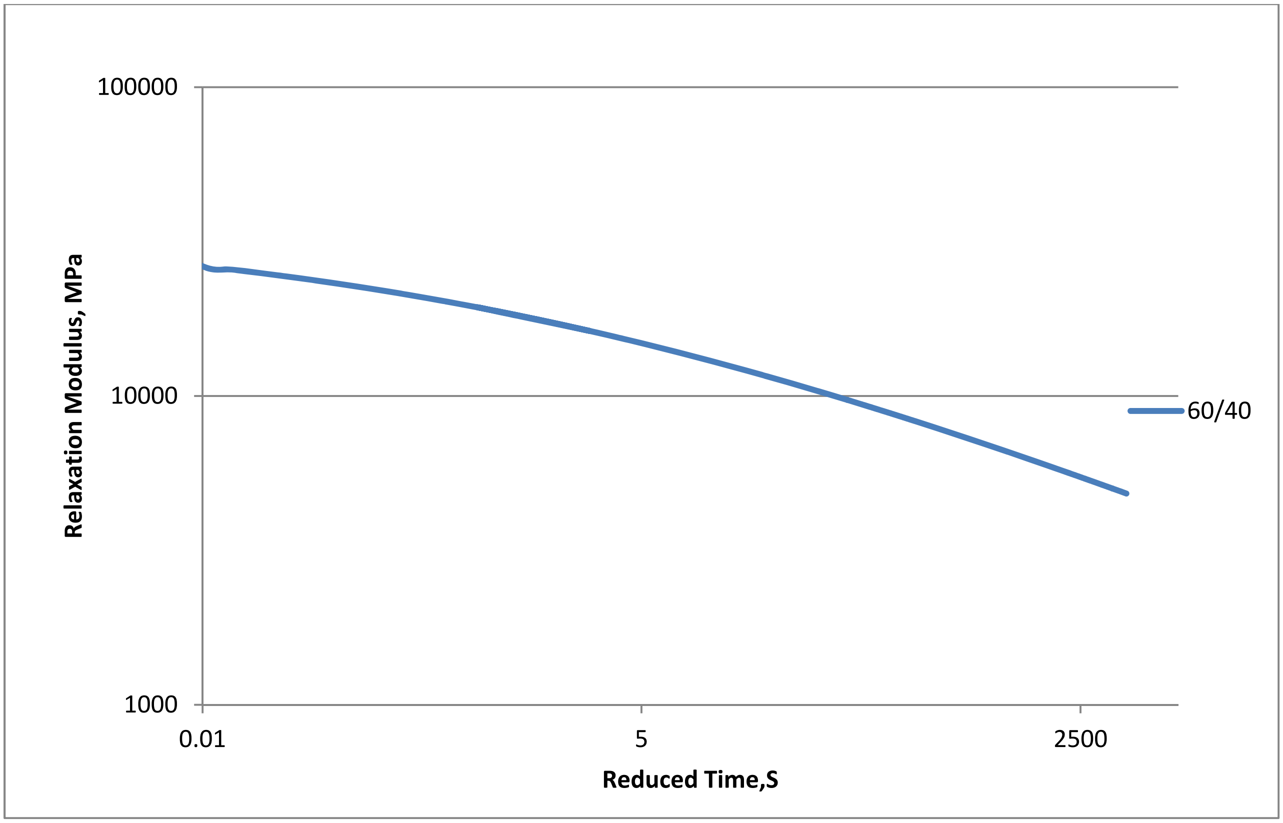

Figure 26-Relaxation Modulus -60/40 Plant Mix

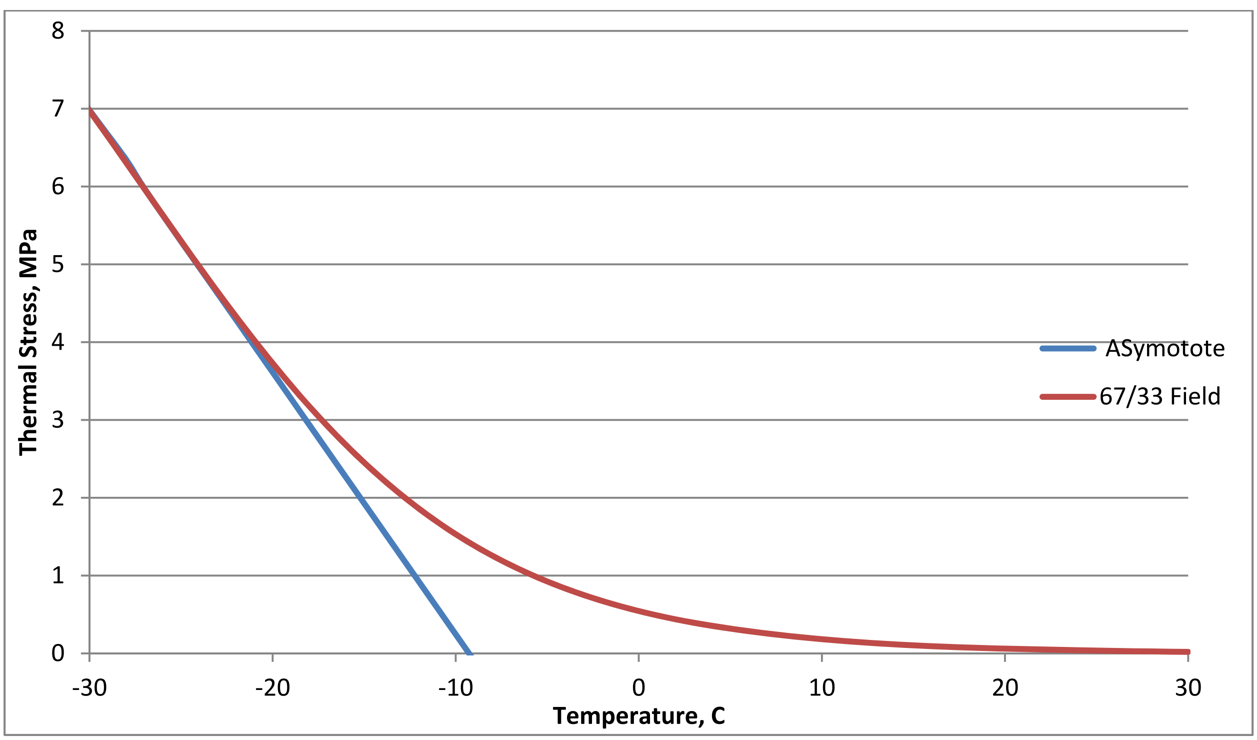

Figure 27-SAP Method-67/33 Plant Mix

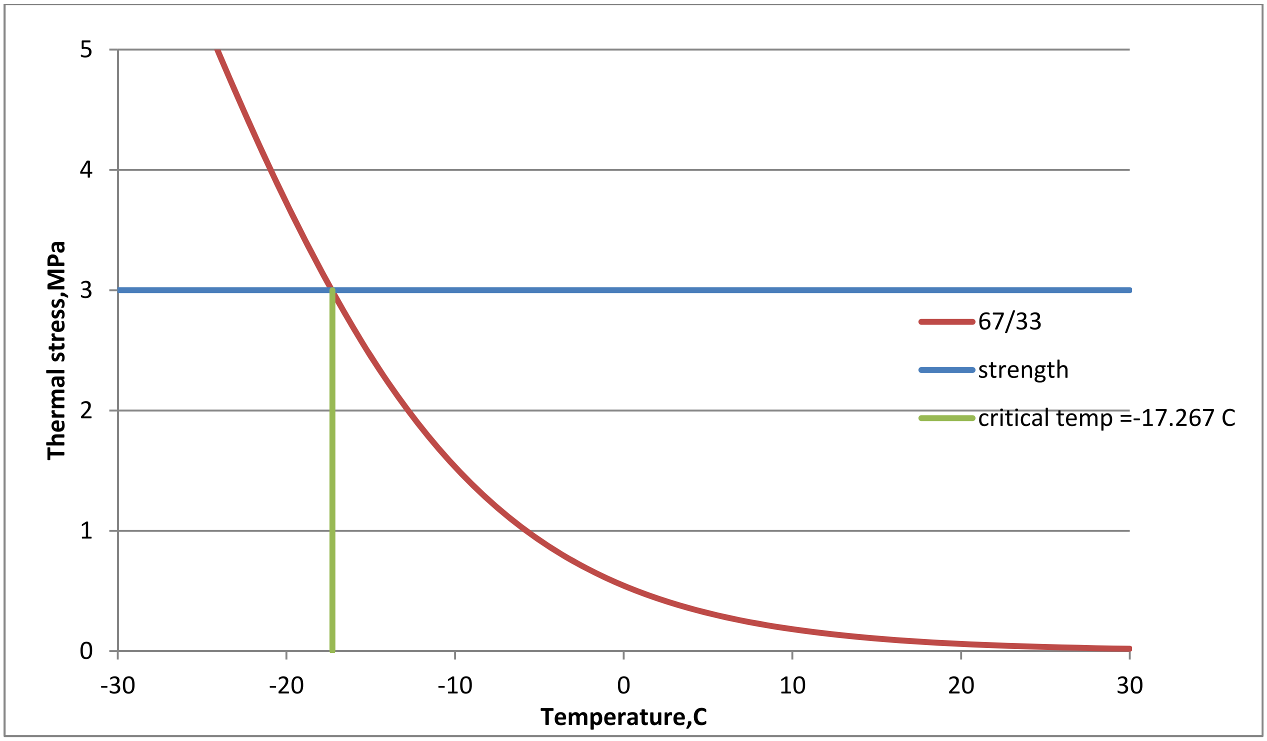

Figure 28-Strength Method-67/33 Plant mix

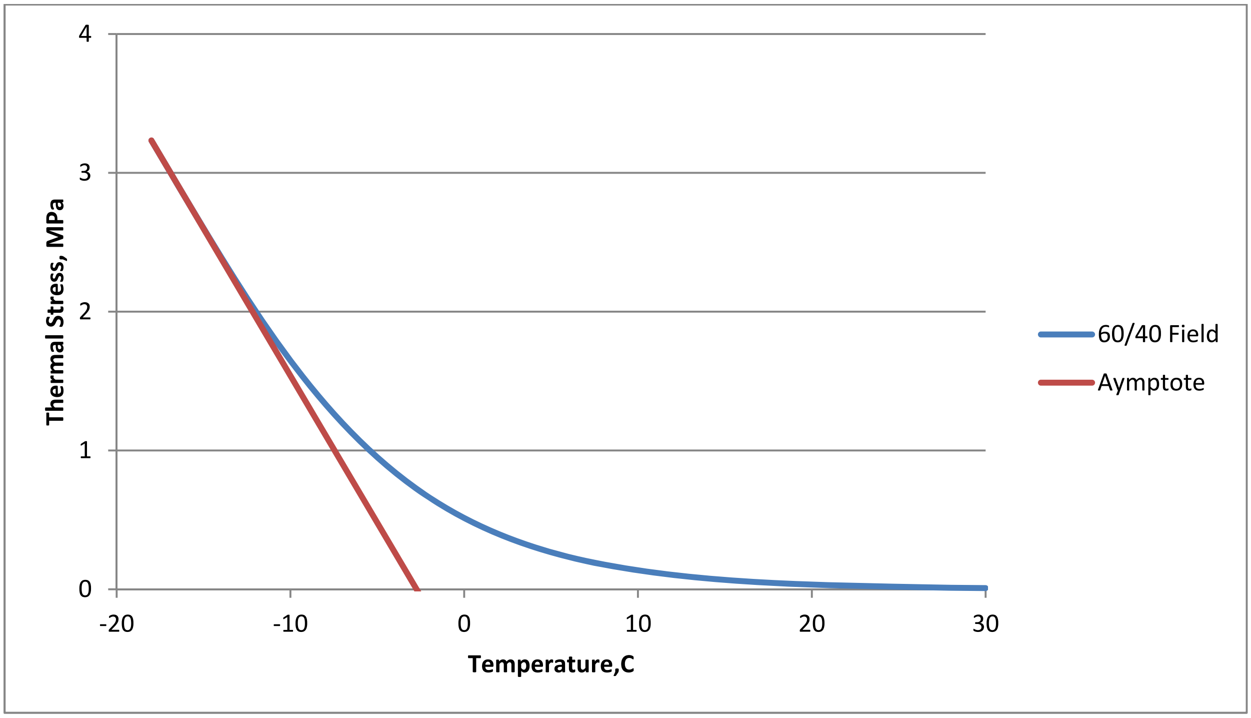

Figure 29-SAP Method-60/40 Plant Mix

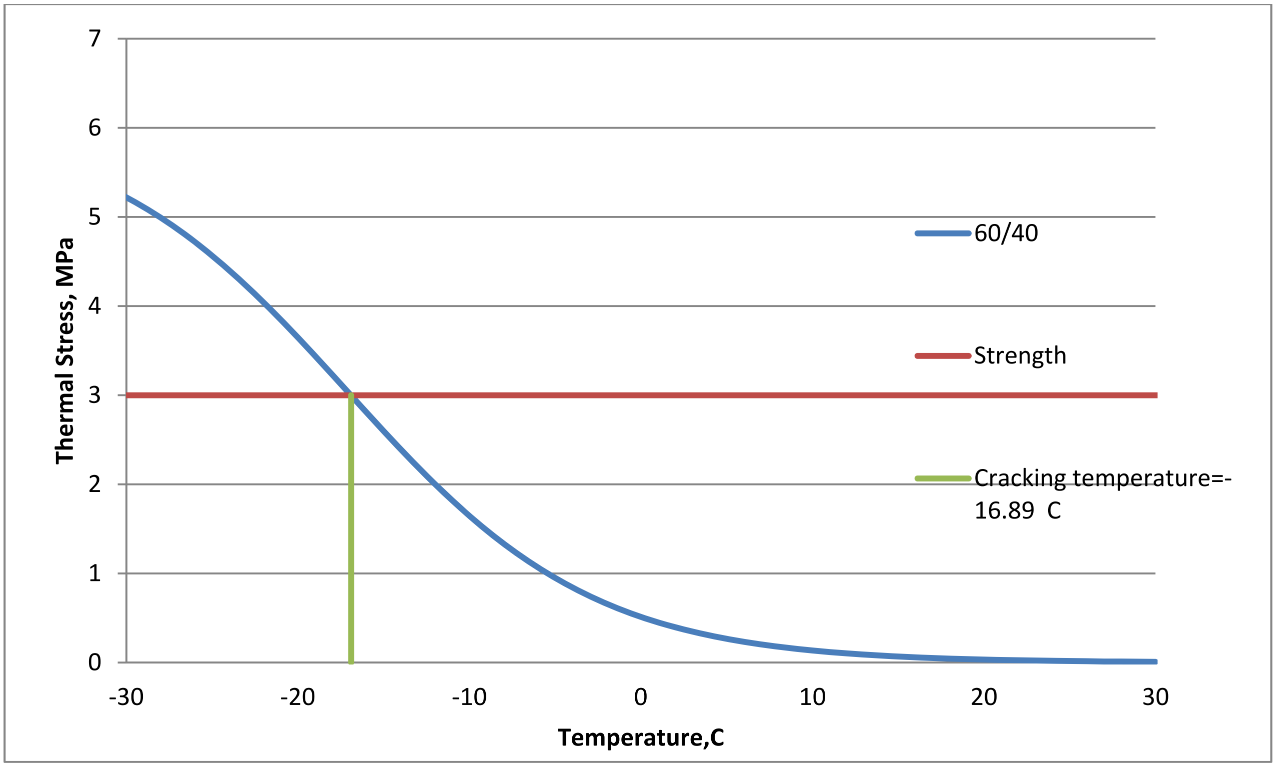

Figure 30-Strength Method 60/40 Plant Mix

The strength of asphalt for determining the critical cracking temperature of plant mixture was taken as 3MPa [22]. A comparison of the TCR values for plant mixtures using the SAP method and Strength Method is provided in Table 10.

Table 10-TCR Comparison for Plant Mixes

Mix Name	TCR corresponding to strength of 3 MPa, ˚C	TCR through single asymptote procedure (SAP), ˚C	Difference in TCR values from strength method and SAP method
67/33 P	-17.27	-9.27	8
60/40 P	-16.89	-2.73	14.16

RESULTS ANALYSIS

As mentioned in the methodology, a set of 15 beams were prepared from each oil sand mix. These samples were tested in the Bending Beam Rheometer (BBR) and the creep compliance values obtained from testing were used to generate master curves. Using the time-temperature super position principle for the master curves, relaxation modulus equation as a function of reduced time was developed. Then using shift factors, this relaxation modulus was developed as a function of temperature, which finally was modified into an equation to find the thermal stress as a function of temperature. This equation was used to generate the thermal stress curves from which the critical cracking temperature was calculated. The critical cracking temperature (TCR) calculated for each mix is shown in Table 11.

Assuming the variance (less than 10%) obtained during testing comes through the analysis, it is believed that these temperatures obtained are within the range of 10%.

Table 11-TCR Comparison-Plant and Lab Mixes

Mix Name	TCR corresponding to strength of 3MPa,˚C	TCR through single asymptote procedure (SAP), ˚C
60/40 P	-16.89	-2.73
67/33 P	-17.27	-9.27
60/40	-6.39	-7.52
67/33	-8.25	-7.35

Hence, the actual cracking temperatures of the mixes are in the range of ±10% of the obtained temperatures.

The lab prepared oil sand samples resulted in different cracking temperatures than the plant produced mixes. This is most likely due to the differences in mixing conditions between lab and plant. The plant mix samples were brought from the road and compacted in the lab whereas the lab samples were compacted without any delay. The aging effect and difference in compaction levels caused due to aging might be one of the reasons for obtaining different cracking temperature. This could be also verified from looking at the variations in densities between plant and lab samples. The plant samples were slightly denser than the lab samples (refer to Table 5), which shows the difference in compaction.

As the percent of oil sand in the samples increase, the relaxation modulus decreases for the same time and temperature. If the relaxation modulus is higher, then the stress on the material is higher at low temperatures. Similarly, if the relaxation modulus is lower, then the stress on the material will be lower. This is because the reaction to temperature drop on the material is a strain controlled type of reaction. From the results, it is observed that percentage of oil sand in the mixture is indirectly proportional to the relaxation modulus of the mixture. Hence, higher oil sand content in the mix might result in the lower relaxation modulus of the mix.

From the thermal stress point of view, it is desirable to have cracking temperature of the material that is lower than the actual temperature of the pavement. If the cracking temperature is higher than the actual low temperature of the pavement, then the pavement will crack due to thermal stress. The cracking temperatures determined in the research were compared to the general low pavement temperatures in Utah. To compare low pavement temperatures with the cracking temperatures, LTPP Bind Software was used. This software was developed by Federal Highway Administration. It is used in finding high and low pavement temperatures in an area with different reliability. Low pavement temperatures in Utah with 50% reliability are shown in Figure 32, which is a screenshot from LTPP bind software. A 50% reliability means that the values in the map represent average temperature, i.e., 50% of the time the temperature will be higher and 50% of the time the temperature will be lower.

Figure 31-Thermal Cracking in Asphalt Pavement

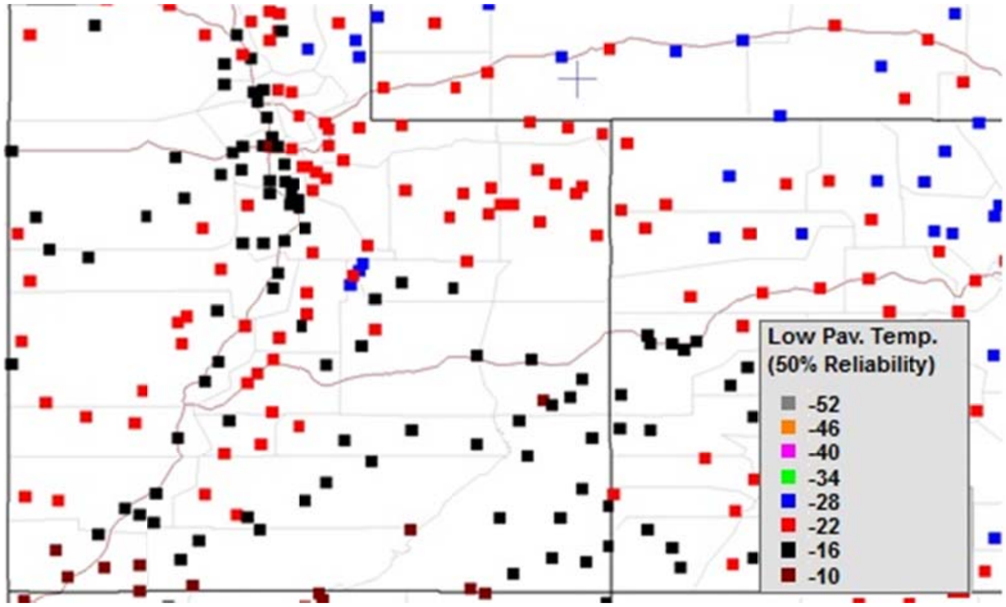

Figure 32-Low Temperatures in Pavements with 50% Reliability

The cracking temperatures determined in the research were lower than -16˚C. These mixes can be used to construct the pavements in the regions where the temperatures are higher than -16˚C, i.e., southern Utah and some regions of Salt Lake area in Figure 32. However, the temperatures shown in the Figure 32 are of 50% reliability, which means there is only 50% chance that the actual temperature will be in the given range. In other words, these temperatures represent the average low temperatures in the pavement. They could be higher or lower than the average temperatures. So, these mixes cannot be used for pavement construction in these areas as it has less reliability. A new map was generated with 98% reliability showing the low pavement temperatures in pavement in Utah and it was compared to the cracking temperatures. Figure 33 shows the low pavement temperatures in Utah with 98% reliability.

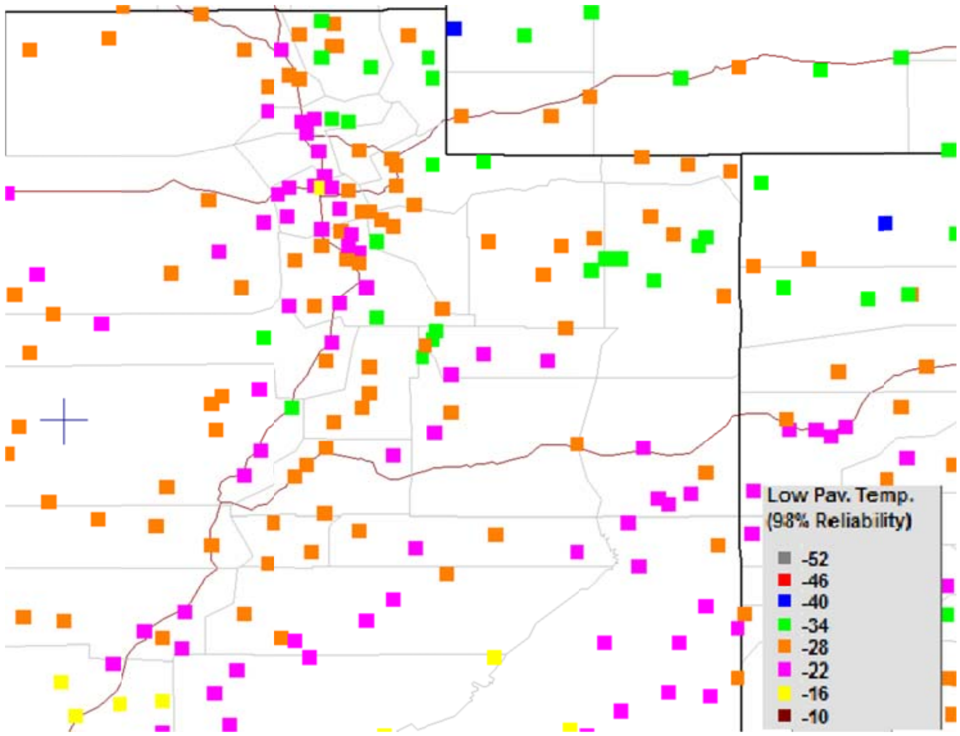

Figure 33-Low Temperature in Pavements with 98% Reliability

From the figure, it is observed that most of the regions in Utah have low pavement temperatures below -16˚C. As the predicted cracking temperatures of the oil sand mixes are higher than the actual low temperatures observed from the map, these mixes will result in thermal cracking if it is used for pavement construction in Utah. Even if we compare the cracking temperatures to the average low pavement temperatures, they are higher than the low pavement temperatures in the majority of the region. So, based on this work, the mix design developed will result in thermal cracking in the Utah region where low pavement temperatures are lower than -16˚C.

Thermal cracking deteriorates the pavements. From the public perspective, this cracking is not noticed unless it damages the surface to an extreme that requires closing of lanes. If these mixes are used in high volume roads (AADT>1000), the traffic would be severely disrupted during maintenance. However, if these mixes are used in roads where there is less AADT (<1000), they would not cause as much inconvenience during the required maintenance.

It is to be noted that construction of pavements with oil sands might have some advantages. The construction cost of roads made with oil sands might be less in some places than the normal asphalt mix roads because the material is available in large quantities and the cost for transporting material to the mixing plant can be less since the material is available locally. The temperature required to heat this mix (220˚F) is lower than conventional asphalt mixes (275˚F-300˚F) and hence it reduces the cost of fuel expenses for heating and also reduces environmental pollution caused due to heating. From this, it can be said that the construction cost of the oil sands mixture pavement can be lower than that of the traditional asphalt mix but it might require higher maintenance than the traditional mix. The choice of using oil sands for pavement construction is beyond the scope of this paper as it involves more economic variables such as cost of material, cost of maintenance, availability of the material. Having said that, construction of pavements with oil sands in places like parking lots and low volume roads (<1000 AADT) might prove to be beneficial economically as their might not cause inconvenience to the public. It is to be taken into consideration that 82% of US. lane mileage accounts for low volume roads [24].

SUMMARY

This research has met the objectives of obtaining the mechanical properties of oil sand mixes and determining the critical cracking temperatures of these mixes. The key findings in the research are:

1. The relaxation modulus of a mix increases as the oil sand percentage decreases,
2. The cracking temperature of 67/33 oil sand mix is -7.35 and -9.27 C for lab and plant mix respectively and
3. The cracking temperature of 60/40 oil sand mix is found to be-7.52 and -2.53 C for lab and plant mix respectively.

Based on the results obtained, the following conclusions and recommendations were made:

Conclusions

1. The mix design prepared from oil sands should not be used for pavement construction in Utah where the low temperatures in pavements were lower than the critical cracking temperatures obtained in the research.
2. The material can be used for construction of roads, which have low AADT volume. Some of this type of roads includes parking lots and rural roads with less

population. These roads have less usage and hence it will be economically beneficial to use oil sands mix for these kinds of roads.

Recommendations

1. The developed mix design is not adequate to resist low temperature cracking in pavements in Utah. In order to make it adequate, further research is needed to modify the material. One way to modify the material is by adding new components into the mix to improve performance. The addition of virgin asphalt binder into the mix may help the material meet performance measures at the temperature ranges of conventional binders, even though the addition of a small amount of virgin binder decreases the economic and environmental gain of the oil sand mix.
2. Another way to improve the material is by the incorporation of material such as Recycled Asphalt Pavements (RAP) and Recycled Asphalt Shingles (RAS) and see whether they help in improving the performance of the material.

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